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The uncapacitated battery swapping facility location problem with localized charging system serving electric bus fleet

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Abstract

This paper considers a refueling system for battery electric buses (BEBs) with battery swapping technology. The service capability of the battery swapping stations (BSSs) is restricted by localized charging system in terms of its charger type and the quantity of both chargers and batteries. The modelling intention is to answer four fundamental questions: How many BSSs should there be? Where should they be? Which BEBs should they serve? How big should they be? In this context, the problem has been formulated as a mixed-integer problem and decomposed into two subproblems. The first subproblem solves the uncapacitated fixed charge facility location problem (UFCFLP) to find the optimal BSSs location and the swapping demand assignment of BEBs. The optimal configuration of localized charging system is developed as integer linear programming problem to decide the charger type and battery inventory in the second subproblem. The solution method is tested on a small network under various parameter settings to investigate the BSS location and configuration and verify the feasibility and effectiveness of the proposed solution approach. Results shows that the battery capacity would affect the number of BSS to locate and the localized charging system configuration mainly depends on the charger and battery costs.

Keywords: battery swapping station; electric buses; facility location problem; localized charging system;

1. Introduction

Battery electric buses (BEBs) are characterized by fixed running routes, fixed depots, near-identical battery capacity. However, configuring an overall BEB system is challenging; this would include possible battery recharging

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and swapping concepts, choice of battery technology, battery sizing, positioning and dimensioning of charging and swapping stations (Leou and Hung, 2017). Comparing to conventional diesel-powered buses, BEBs still suffer from long charging time, limited mileage range, and insufficient charging infrastructure regardless of its regenerative braking attribute.

Typically three charging methods are available at current stage, namely slow charging, fast charging and battery swapping. Slow charging usually takes hours to refuel and reduces the utilization of BEBs, while fast charging reduces battery life (Sarker et al., 2013). It is pointed out that EV's orderly charging is the prerequisite for realizing its environmental benefits especially in countries with fossil-dominated power and the disordered charging will cause load fluctuations, and increase generation costs (Rao et al., 2015).

The deployment of battery swapping stations (BSSs), which removes the depleted batteries on the BEBs and replace the batteries with fully charged ones, is an alternative strategy to eliminate these barriers (Avci et al., 2014). The most outstanding feature of this strategy is that BSSs can complete the swapping process in less than 10 min, while another advantage is that charging the depleted battery can be left for the night at a discounted electricity price. Since BSSs achieve a unified management of batteries, it contributes to the effective maintenance of batteries and is beneficial to extend the batteries' lifetime. However, due to the lack of standardization of batteries and interfaces, the BSSs are more suitable for fleets of buses and taxies (Zheng et al., 2014).

Theoretically BEBs can travel up to 250 km, various factors influence the operational range in the real-world operations. It is shown that the air conditioning, driving behavior and battery aging issue can largely (more than 30%) reduce the BEBs' operational range, thus making BEBs often incapable of finishing a whole day's work without battery recharging (Li, 2016). Moreover, BSSs require large capital investment to purchase additional batteries that are necessary to swap with ones near depletion. The land-use is another issue, including the parking space for bus awaiting and the space for installing local chargers on spot for localized charging mode (Li, 2016). Therefore, the location of BSSs and the choice of charger types become an inevitable issue when designing battery swapping system due to their charging speed and financial cost.

To promote development of BSSs for BEBs, the optimal BSSs' location and its local charging system design should be researched first and the major factors affecting the capital investment for the stakeholder should be fully considered in the process of planning. Moreover, transport cost between BEB transit depot and BSSs would also be one of the major concerns because of range limit and the energy waste during the detour to swap the depleted battery.

In this paper, we propose an optimization framework of locating uncapacitated BSSs involving the localized charging system planning. Comparing with previous studies, the main contributions and differences of this paper can be summarized as follows. First, to our best knowledge, this is the first study investigating the deployment of BSSs with different types of localized charging infrastructure while taking into account total battery and charger costs. Second, the proposed model can be decomposed into the fixed charge facility location model and an integer linear programming problem which can be easily solved separately. Third, the optimal number of batteries and chargers and the type of chargers initially purchased at each candidate BSS site are also be decided through the proposed model to satisfy the swapping and charging demand of BEBs.

This paper is organized as follows. Section 2 introduces the basic consideration of the minimization model. Section 3 discusses the mechanism of uncapacitated BSSs with localized charging system and its mathematical formulation. The solution method is shown in Section 4. In Section 5, we use a case study to demonstrate the effectiveness of the proposed solution method. Finally, Section 6 is devoted to the conclusions and future research.

2. Basic consideration

Facility location decisions are strategic in nature. The BSSs to be located with its localized charging system will remain in place for many years. Tactical and operational decisions of BSSs are dependent on the locational decisions. The conditions and policies under which the BSSs will operate in the future are not known with certainty. In particular, the swapping demand of the BEBs, the service capability and costs associated with charging technology, the costs and capacity with batteries, and the potential stakeholders and operation mode of the battery charging scheduling may all be subject to uncertainty, thus it is often unwarranted to insist on strict satisfaction of battery quantity constraints. Since the intent of this paper is to explore a location model regarding the newly-emerging battery charging and swapping system for BEBs, we adopt some simplified settings to deploy the BSSs with localized battery charging system for serving BEB transit depot. Considerations and assumptions of the modeling framework are summarized as follows:

1. The service capacity of a BSS is considered to be unlimited, i.e., BSS itself is uncapacitated.
2. All BEBs are using uniform type of batteries.
3. Battery swapping service frequency is identical for all BEBs with the same battery capacity.
4. The BEB operation scheduling and optimal arrival pattern is not considered here.
5. The service time period for both battery swapping and charging are the same, i.e., BEB operation time and battery charging time are equal.
6. BEBs go to BSSs from the transit depot only and they do not need swapping service on route.
7. Every BEB can get a fully charged battery when they arrive at the BSSs.

3. Model formulation

Typically, BEB company or power grid company is the major investor to build the BSS network and decide the location and configuration (in terms of charger type, charger quantity, and battery inventory) of BSSs, aiming to reduce the total investment of BSSs network serving BEBs. Therefore, this paper intends to minimize the total system investment, including fixed swapping facility costs, total routing costs between BEB transit depot and BSSs, initial batteries purchase cost and charger installation cost.

The following lists notation of variables and parameters used throughout this paper.

Variables and parameters	Description
f_j	fixed cost of constructing charging facility at candidate site $j, j \in J$
X_j	binary variable, equals 1 if there is a BSS at candidate site $j \in J$, 0 otherwise
γ	conversion coefficient, cost per unit distance per swapping demand
n_i	number of BEBs at transit depot $i, i \in I$
m	swapping service frequency for BEBs at transit depot in a typical service period
h_i	swapping demand at transit depot $i \in I$, $h_i = n_i m_i$
d_{ij}	distance between transit depot i and candidate BSS site j
Y_{ij}	assignment variable, fraction of demand at transit depot i that is assigned to a BSS at candidate site j
c_t	the installation cost of a charger type t , including area covered, transformer and power lines
n_{tj}	the number of charger type t at candidate site j
c_b	the cost of purchasing a battery
n_{bj}	the number of battery used at candidate site j
S_t	service capability of charger type t in a typical service period

Objective function:

$$\min \sum_j f_j X_j + \gamma \sum_i \sum_j h_i d_{ij} Y_{ij} + \sum_j \sum_t c_t n_{tj} + \sum_j c_b n_{bj} \tag{1}$$

s.t

$$\sum_j Y_{ij} = 1, \forall i \tag{2}$$

$$Y_{ij} \le X_j, \forall i, j \tag{3}$$

$$X_j = \{0,1\}, \forall j \tag{4}$$

$$Y_{ij} \geq 0, \forall i, j \tag{5}$$

$$S_t \geq 1, \forall t \tag{6}$$

$$\sum_i h_i Y_{ij} \leq \sum_t n_{tj} S_t X_j, \forall j \tag{7}$$

$$\sum_i n_i Y_{ij} \leq n_{bj} \leq m \sum_i n_i Y_{ij}, \forall j \tag{8}$$

$$m \geq 1 \tag{9}$$

$$n_{bj} \geq \max_t \left\lceil \frac{m}{S_t} \right\rceil \cdot \sum_i n_i Y_{ij} - \sum_t \left\lfloor \frac{S_t}{m} \right\rfloor \cdot n_t \cdot (\max_t \left\lceil \frac{m}{S_t} \right\rceil - 1), \forall j \tag{10}$$

The objective function (1) is to minimize the sum of the cost for building battery swapping stations, transportation cost between demand point (electric buses depot) and battery swapping stations, charger cost and battery cost. Constraint (2) requires that every EB at hub i to be assigned to exactly one single BSS, while constraint (3) ensures EB assignments to only open battery swapping facilities. Constraint (4) and (5) are the integrality and nonnegativity constraints for location variables ($\mathbf{X}$) and assignment variables ($\mathbf{Y}$). Constraint (6) states that each charger can fully charge at least one battery during a typical service day. Constraint (7) indicates that the total demand assigned to site j should not exceed its charging capability at this site. Also, there should be enough batteries in order to make sure every charger is charging the depleted battery round-the-clock. Constraint (8) limits the number of batteries stored at site j . The lower bound ensures every BEB can get a battery even if they arrive at the BSS at the same time in the worst case scenario of BEB arrival pattern. The upper bound limits the battery quantity to the total swapping service demand assigned to the BSS considering constraint (6). The battery swapping service frequency is set in constraint (9). During a typical operation day, BEB arrives at BSS m times for swapping service. It is understandable that the time before which the slowest charger installed can fully charge a depleted battery requires most batteries in a day. Constraint (10) considers this worst ca

se scenario of battery quantity requirement. The floor function $\lfloor x \rfloor$ is the function that takes as input a real number x and gives as output the greatest integer that is less than or equal to x . Similarly, the ceiling function $\lceil x \rceil$ maps x to the least integer that is greater than or equal to x . The first term on the right-hand side of constraint (10), $\max_t \left\lceil \frac{m}{S_t} \right\rceil \cdot \sum_i n_i Y_{ij}$ is the total swapping demand for the worst case scenario if none batteries have been used repeatedly. $\max_t \left\lceil \frac{m}{S_t} \right\rceil$ is to calculate the worst case scenario where BEB fleet arrival requires the most batteries so far accumulatively. The second term $\sum_t \left\lfloor \frac{S_t}{m} \right\rfloor \cdot n_t \cdot (\max_t \left\lceil \frac{m}{S_t} \right\rceil - 1)$ is the number of batteries that have been fully charged and reused during the operation.

4. Solution method

In order to reduce the complexity of the problem, the location and configuration of BSS are decided separately in this paper, which decomposes the original problem into two sub-problems. First, BEB companies intend to minimize the fixed BSS investment cost at the candidate site including land and building construction cost and total transport cost between BEB transit hub and BSSs without consideration of the specific BSS configuration. Through the first stage, the BSS location (X) and the assigned swapping service demand (Y) can be determined. In this paper, GUROBI with python interface is applied to solve the proposed two sub-problems.

The mechanism of deciding BSSs' optimal configuration is shown in Fig. 1. In the second sub-problem, based on the assigned demand and the service capability and price of different chargers, the optimal numbers of batteries and chargers, and the type of chargers initially installed can also be determined through the proposed model to minimize the total cost while satisfying the swapping service demand at each site.

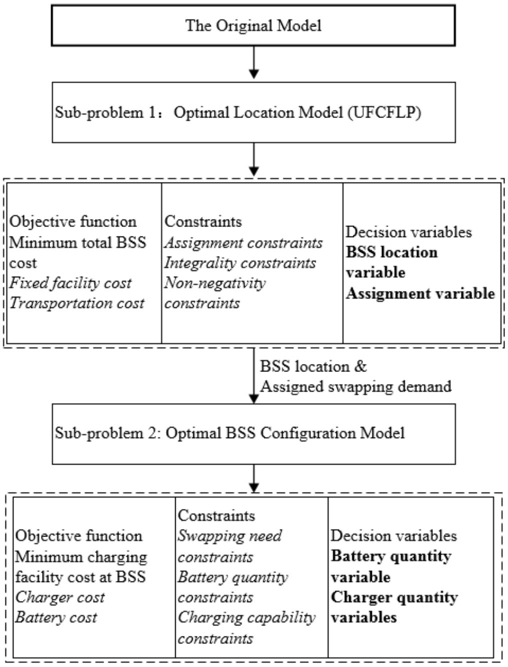


Fig. 1. The uncapacitated BSS location problem with localized charging system.

5. Case study

This section presents a small numerical case study to assess the performance of the proposed method. The first example represents some pilot battery swapping programs for BEBs which serve several bus routes with limited number of vehicles and candidate sites. In our experience, the number of BSSs in a given region is frequently orders of magnitude less than the number of BEB transit depot. A region may have a dozen transit depots and over hundreds of buses in service.

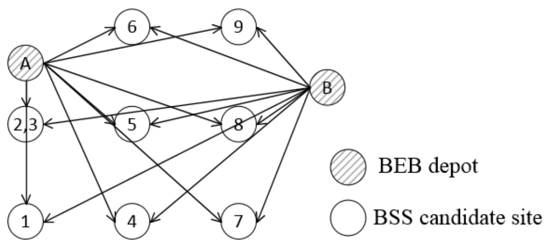


Fig. 2. Small example with 2 BEB depots and 9 BSS candidate sites.

The example, whose spatial distribution is shown in Fig. 2, consists of 2 BEB transit depots, 9 candidate BSS sites. The distance matrix shown in the last four columns in Table 1 between BEB transit depot and candidate BSS site is introduced from implementation data of GUROBI example, where normally the BEB transit depot and BSS are not far from each other to reduce the unnecessary energy loss. The values of charger costs are inspired by the current charger purchase price and charging capabilities are based on three currently available charging speed levels. To facilitate the presentation of this small example, Table 1 summarizes the parameters used. The optimal solution to this small problem is $\mathbf{X} = \{0,1,0,0,0,0,0,0,0\}$, $\mathbf{Y} = \{0,1,0,0,0,0,0,0,0;0,1,0,0,0,0,0,0,0\}$. Clearly, the only BSS is built at candidate site 2 and all the demand at BEB depots A&B must be assigned to the single BSS with the deployment of $n_1 = 0$ slow chargers, $n_2 = 30$ fast chargers and $n_b = 30$ batteries. The total cost is composed of 200 fixed cost, 140.32 transportation cost, 120 battery cost, 280 charger cost. As we can see in this case, the number of fast charger and that of slow charger ranges from 0 to 3 and 60 to 0 respectively to satisfy daily charging demand. Adding one fast charger is equivalent to reducing 20 slow chargers and 10 batteries. The specific local charging system depends on the tradeoff of the input parameters including demand, battery cost, charger cost and charging capability.

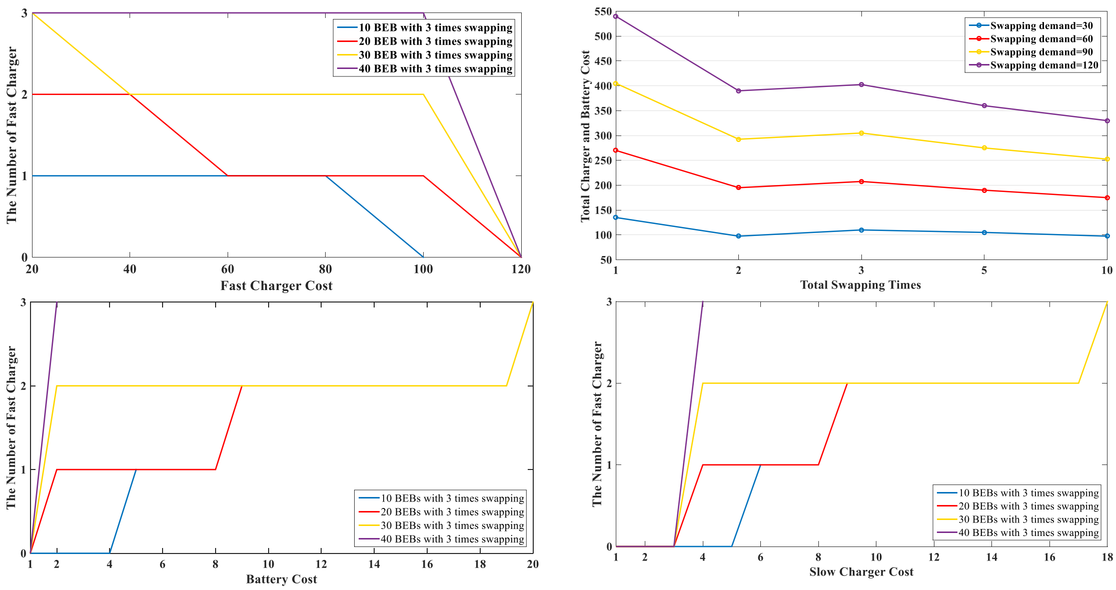
Battery capacity can affect the BSS location decision by influencing the total transportation cost. When battery capacity is relatively limited or BEB companies are making a strategic long-term planning, they value more on reducing the energy loss due to the detour between BSS and BEB depot. In this case, a bigger γ value means putting more weight on transportation cost. When increasing the γ value to 5, based on the parameters in Table 1, the number of the deployed BSS becomes 2, locating at node 2 and 8 and demand A and B are assigned to node 2 and 8 respectively.

Table 1. Basic model input.

Parameters	Values				
f_j	300, 200, 300, 200, 300, 300, 400, 300, 200	d_{A1}	1.50	d_{B1}	2.77
m	4	d_{A2}	0.50	d_{B2}	2.51
n_i	20, 10	d_{A3}	0.50	d_{B3}	2.51
γ	1	d_{A4}	1.80	d_{B4}	1.92
d_{ij}	See rightside columns	d_{A5}	1.12	d_{B5}	1.51
S_t	2, 40	d_{A6}	1.12	d_{B6}	1.70
c_t	4, 100	d_{A7}	2.50	d_{B7}	1.30
c_b	2.5	d_{A8}	2.06	d_{B8}	0.54
		d_{A9}	2.06	d_{B9}	0.94

In the foreseeable future, with the advancement in battery and charger technology, several other factors, such as charger price and battery price, will probably vary in different way. In scenarios a), the parameters S_t and c_t are the same as those in Table 1. The impacts of battery and chargers cost on charger selection are examined in Fig. 3 under different demand scenarios. The number of fast charger is chosen as the y axis for its reasonable range (0, 3). As can be seen in case (a) of Fig. 3, the preference of using fast charger increases with the battery cost. In addition, one fast charger (red line) or two (yellow line) works better with a few more slow chargers when their charger cost difference is huge. However, if battery is very costly, the company will prefer fast charger for its capability of improving the battery utilization rate. From case (b) & (c), the BEB arrival pattern is fixed when fixing the total times of swapping. For the yellow line, the total demand equals to 90 while 2 fast chargers can only satisfy 80 demand. In order to satisfy the remaining 10 demand, the slow charger cost has to climb to 18 so that the planner would adopt 3 fast chargers configuration and abandon 5 slow chargers with 2 fast chargers, along with 3 less batteries. This phenomenon occurs when fast charger results in redundant charging capability.

(a) The impact of battery cost on the charger selection under different demand (left)
(b) The impact of slow charger cost on the charger selection under different demand (right)



(c) The impact of fast charger cost on the charger selection under different demand (left)
(d) The impact of swapping frequency, BEB quantity on BSS configuration cost (right)

Fig. 3. Sensitivity analysis of key factors.

The impact of different swapping demand combination (BEB quantity H multiply by swapping times m) on the BSS charging system configuration cost is shown in (d) Fig. 3, in which 20 combinations are categorized into 4 levels of swapping demand. If the first subproblem of UFCFLP is based on the assignment of swapping demand, any level of swapping demand has different combination with its optimal charger and battery cost. The number of BEB drops with the increase of swapping times for every fixed swapping demand. Comparing the combinations of each demand line, its total charger and battery cost basically decreases with the amount of BEBs due to the change of charger combination or battery inventory. The only exception breaking this tendency is when swapping frequency equals to 2.

Take swapping demand 30 for example. The amount of battery needed experiences a sudden drop when $m = 2$, because the charging capability of the installed slow charger also equals to 2. Every charger keeps working and every fully charged battery will be immediately swapped into the BEB. In other words, the BEBs arrive at the BSS right after the 15 depleted batteries are fully charged, thus the charging system works perfectly with the BEB arrival pattern. We can also see that no fast charger is used for this case. Because it is uneconomic to install a fast charger considering its cost and charging capability, i.e. $C_1/S_1 = 2$ and $C_2/S_2 = 2.5$. For swapping demand 90, when the swapping frequency climbs and BEB quantity decreases, fast charger can largely reduce the total number of battery in the localized charging system by increasing the battery utilization rate. It is expected that fast charger would be preferred more than slow charger when battery cost remains high and BEB swaps more frequently. However, in real world, the swapping frequency and BEB amount will remain in a reasonable range. Therefore, 18 BEBs with 5 times of swapping or 30 BEBs with 3 times of swapping is more realistic over 9 BEBs swapping 10 times.

Table 2. Localized charging system configurations of scenarios (a) swapping demand =30 (b) swapping demand =90

BEB quantity	H	30	15	10	6	3	90	45	30	18	9
Swapping frequency	m	1	2	3	5	10	1	2	3	5	10
Battery and charger cost		135	97.5	110	105	97.5	405	292.5	305	275	252.5
Slow charger quantity	n_1	15	15	15	15	15	45	45	5	5	5
Fast charger quantity	n_2	0	0	0	0	0	0	0	2	2	2
Battery quantity	n_b	30	15	20	18	15	90	45	34	22	13

6. Conclusion and further work

The refueling system of BEBs needs a specific investment optimization. As a promising solution to refuel the BEBs, this paper establishes a simple novel method to minimize the cost and evaluate BSS location problem with its localized charging system configuration problem. Four key questions that the BEB company concerns most are answered: 1) the location of BSS; 2) the assignment of BEB swapping demands; 3) the charger selection in terms of type and quantity; 4) the number of battery needed in each BSS. The results show that the proposed method can optimally solve the problem by decomposing it into a fixed charge facility location problem and an integer linear programming problem. Moreover, the study of the localized charging system configuration problem can provide the foundation for designing the optimal combination of chargers and dealing with operation of BEBs in worst case arrival pattern scenario. As a base model with simple assumptions, future work should consider more realistic scheduling of electricity-price-based battery charging and BEB operation to increase the utilization rate of batteries. Furthermore, comparing with localized charging system, models of centralized charging system should be created to make an economic comparison to identify a favorable charging mode. Additionally, the battery capacity and the charging power of BEB used for public transportation are several times greater than that of electric cars, which can result in high energy consumption and negatively impact on power distribution networks. Therefore a BSS deployed at a given region should be considered as capacitated before power grid upgrade to accommodate more local charging demand.

Acknowledgements

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